Geoacoustic Parameters of Marine Sediments: Theory and Experiment

M. J. Buckingham
Marine Physical Laboratory, Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive, La Jolla, California 92093-0238, USA
phone: (858) 534-7977 fax: (858) 534-7461 email: mjb@mpl.ucsd.edu

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LONG-TERM GOALS

There are four long term goals, as follows, in descending order of priority. 1) Characterize fully, from a physics-based model, the inter-relationships that exist between the geo-acoustic properties (*i.e.*, compressional-wave speed and attenuation, shear-wave speed and attenuation, frequency, density, porosity, grain size, grain shape and overburden pressure) of saturated, unconsolidated granular media such as marine sediments. 2) Develop a deep-diving acoustic monitoring system capable of operating to the greatest depths in the ocean. 3) Relate the bubble structure to the acoustic properties of ship wakes. 4) Detect extremely high-energy neutrinos from their acoustic signatures in the ocean.

OBJECTIVES

The scientific objectives of the sediment research may be conveniently divided into five categories. (1) Incorporate the effects of pore fluid viscosity into my analytical theory of wave propagation in saturated granular materials. (2) Continue developing my recently introduced Doppler geo-spectroscopy measurement technique for estimating the geo-acoustic properties of marine sediments using a high-Doppler airborne sound source. (3) Develop analytical and numerical models of wave propagation in a 3-layer waveguide (atmosphere-ocean-sediment) from a moving airborne sound source. (4) Develop inversions, based on the 3-D numerical forward model, for extracting sediment parameters and sub-bottom structure from Doppler geo-spectroscopy data. (5) Identify the relationship between the geometrical properties of individual grains (*e.g.*, size and shape) and the physical properties (*e.g.*, porosity) of the bulk granular material.

The objective of the deep ambient noise project is to develop and deploy a broadband (0.05 - 60 kHz), multi-sensor system capable of monitoring sound to the deepest depths (11,000 km) in the ocean. The system will return depth profiles of the noise level and noise coherence in the vertical.

The objective of the ship-wake research is to relate the strong spatial variability of the void fraction to the acoustic properties of the bubbly wake.

The neutrino detection project is a high-risk, high return venture with Prof. Giorgio Gratta and his research group at Stanford. The objective is to detect extremely high-energy neutrinos, of uncertain extra-terrestrial origin, from their acoustic signatures in the ocean.

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14. ABSTRACT
There are four long term goals, as follows, in descending order of priority. 1) Characterize fully, from a physics-based model, the inter-relationships that exist between the geo-acoustic properties (i.e., compressional-wave speed and attenuation, shear-wave speed and attenuation, frequency, density, porosity, grain size, grain shape and overburden pressure) of saturated, unconsolidated granular media such as marine sediments. 2) Develop a deep-diving acoustic monitoring system capable of operating to the greatest depths in the ocean. 3) Relate the bubble structure to the acoustic properties of ship wakes. 4) Detect extremely high-energy neutrinos from their acoustic signatures in the ocean.

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APPROACH

Sediments

1) Pore-fluid viscosity and the grain-shearing theory of sound waves and shear waves sediments

In the original version of my grain-shearing (GS) theory of waves in saturated porous materials, effects due to the viscosity of the pore fluid were neglected. Such effects manifest themselves at lower frequencies, below 10 kHz, which is well below the frequency band of many of the published measurements of wave properties of sediments. In an effort to fill the low-frequency gap, one component of the ONR-supported SAX99 experiment, conducted in the northern Gulf of Mexico, off Fort Walton Beach, was aimed at extending the frequency range of sound speed and attenuation data to the band below 10 kHz. The new, lower-frequency measurements returned a sound speed (attenuation) that is somewhat lower (higher) than predicted by the GS theory. To accommodate these observations, the GS theory was extended by incorporating the viscosity of the microscopically thin layer of pore fluid separating contiguous grains. The generalized form has been designated the VGS theory, where the first initial serves as a reminder that viscous effects are now included in the model. At higher frequencies, above 10 kHz, the VGS dispersion curves approach those of the GS theory asymptotically; and at lower frequencies, below 10 kHz, the VGS theory shows a very reasonable match to the SAX99 dispersion data. The VGS theory fits the available dispersion and attenuation data over the approximate frequency range 1 - 400 kHz.

2) Doppler geo-spectroscopy

This recently introduced technique for measuring the low-frequency (80 Hz to 1 kHz) sound speed in marine sediments relies on a high-speed airborne sound source (a light aircraft) for ensonifying the ocean and sediment. Most of the received sound is in the form of engine and propeller harmonics, whose frequencies extend from about 80 Hz up to 1 kHz. As the source approaches toward (recedes from) the sensor station, the harmonics are Doppler up-shifted (down-shifted). Normal modes are excited in the water column and are detected on our autonomous line array of 11 non-uniformly spaced hydrophones (known as the “FlyBy array”). A high-resolution spectrum of a single harmonic exhibits sharp peaks, representing the Doppler up- and down-shifted modal field. The magnitude of the modal shifts depends on the speed of the source and the properties of the sea bed. From a precision measurement of the shifted modal frequencies, an inversion returns the sound speed in the sediment; and the remaining geo-acoustic parameters are determined from their correlations with the sound speed, which are known from the VGS theory. Two of my graduate students, Eric Giddens (who now has his Ph.D.) and Melania Guerra, have been directly involved in our Doppler geo-spectroscopy research, along with my engineer, Fernando Simonet. One of my earlier graduate students, Dr. Thomas Hahn, who now holds a faculty position at the University of Miami, assisted us during our participation in SAX04. One of my current graduate students, David Barclay, participated in the Doppler geo-spectroscopy component of the MAKAI experiment, conducted off the western tip of Kauai.

3) Theoretical models of sound from a moving source in a 3-layer waveguide

Two analyses of sound in a 3-layer waveguide (atmosphere, ocean and sediment) from a high-Doppler, horizontally moving, unaccelerated airborne source have been developed based on multiple integral transforms in conjunction with appropriate boundary conditions. The first is a 2-D model (horizontal line source perpendicular to the source track), which yields an exact analytical solution for the field in all three layers, including a new 3-layer dispersion relation that takes account of all the Doppler shifts introduced by the moving source. The second is a 3-D model (point source), whose solution is a double wavenumber integral that is evaluated numerically. Both field solutions exhibit interesting fore-aft asymmetries, which appear to be consistent with the geo-spectroscopy experimental observations.

4) Geoacoustic inversions for Doppler geo-spectroscopy

Based on a comparison of the predictions from the 3-D, double-wavenumber integral model and the data obtained from our Doppler geo-spectroscopy experiments, a “best match” is obtained, from which the sediment parameters are estimated. Essentially, a cost function is formed and minimized. This work was started by my (then) graduate student, Eric Giddens and is being continued by David Barclay.

5) Grain shape and sediment porosity

Of all the physical properties, it could be argued that the porosity of a sediment is the most important in determining its wave properties. The porosity is related to the mean grain size, although not uniquely, suggesting that another parameter is involved, perhaps grain shape or roughness. By examining the shapes of individual grains under a microscope, with careful analysis of the resultant computer-generated images, the relationships between mean grain diameter, rms roughness and bulk-sediment porosity are being investigated. This work is being performed by my graduate student, David Barclay.

Deep ambient noise

This is a new project in which two Vitrovex glass hemisperes, of approximately 0.4 m internal diameter, form a complete sphere containing data acquisition and storage electronics. Throughputs connect external hydrophones and pressure/temperature sensors to the interior of the sphere. As the system descends into the ocean under the influence of gravity at a terminal speed of about 1 m/s, the broadband (0.05 - 60 kHz) ambient noise is detected on two hydrophones, separated vertically by about 0.5 m. At the lowest point in its descent, which may be as deep as 11,000 m, a drop weight is released via a burn wire, and the system returns to the surface under its own buoyancy. Recovery will be achieved with the aid of an Argos antenna, an RF locator beacon and a high-intensity strobe light.

Ship wakes

Aerial photography using a 35mm Canon 5D camera returns high-resolution (12.8 Megapixel), high-dynamic-range (16-bit) digital images of the bubbly wake produced by various types of maritime vessel. In such images, the detailed geometrical shape of the bubbly wake can be observed, as can the pronounced patchy structure of the bubble concentration along the length of the wake. By extracting the spatial statistics of the void fraction distribution from the images, a numerical model of the “acoustic” wake is being constructed, which will be incorporated into 3-D numerical acoustic propagation/scattering models.

Neutrino detection

Particle physicists have theoretical reasons for believing that extremely high energy (non-solar) neutrinos should exist. Since such particles possess mass, they interact with matter, including the ocean, where they deposit energy, causing thermal expansion, which results in a brief burst of sound. Working in conjunction with Prof. Giorgio Gratta and his research group at Stanford, we are using the US Navy’s AUTEC array of bottom-mounted hydrophones off Andros Island, Bahamas in an attempt to detect neutrino sound signatures. AUTEC is located in the Tongue of the Ocean, which is relatively quiet, since it is protected from shipping noise. However, over the bandwidth of the detection system (approximately 50 kHz), there are plenty of sources of ambient noise, including marine mammals. Much of the effort to date has been directed at characterizing this background noise, against which the neutrino signals must be detected.

WORK COMPLETED

Sediments

1) Pore-fluid viscosity and the grain-shearing theory of sound waves and shear waves sediments

The VGS theory has been completed and its predictions compared with the dispersion and attenuation data from SAX99, as shown in Fig. 1. The new theory has been published in the September 2007 issue of *Journal of the Acoustical Society of America*.

2) Doppler geo-spectroscopy

During September 2005, as part of the ONR-sponsored MAKAI experiment, conducted off the west coast of Kauai, we performed Doppler geo-spectroscopy experiments using our Fly-By line array of 11 non-uniformly spaced hydrophones. The array was deployed either horizontally on the seabed, aligned parallel with the depth contours, or vertically in the water column. A light aircraft (Maule MXT7-180 STOL), rented from a local tour-flight company at Lihue airport, was used as the sound source. Multiple low-level flights were made over the sensor station, yielding a variety of interesting data sets. A further set of flying experiments was conducted at a deeper site, close to the Kilo Moana, the research ship participating in MAKAI. At this location the Fly-By array was deployed vertically. Along with the Doppler shifted acoustic signature of the aircraft, the Fly-By array recorded ambient noise at both sites, although most of the time the weather was calm, as a result of which the noise intensity was almost undetectably low.

3) Theoretical models of sound from a moving source in a 3-layer waveguide

Both models are complete and have been published in the October 2006 issue of the *Journal of the Acoustical Society of America*.

4) Geoacoustic inversions for Doppler geo-spectroscopy

Refinements to the geo-acoustic inversion procedure have continued, including the development of a high-resolution, adaptive filtering technique for enhancing the modal peaks in the Doppler-shifted spectrum.

5) Grain shape and sediment porosity

This work is progressing, based on photomicrographs of various types of grains collected from different locations worldwide.

Deep ambient noise

The data acquisition and storage electronics have been designed and fabricated. The circuits have been assembled into the Vitrovex sphere, along with pressure and temperature sensors. Standard ITC hydrophones (with depth rating of only 1000 m) have been installed external to the sphere on a specially designed support frame. The recovery antennas are not yet available, nor are the deep-diving hydrophones. Salt-water tank tests on the stability of the system and its descent rate have been satisfactorily performed. The system works exactly as required.

Ship wakes

Aerial photographs of ship wakes have been taken routinely during flights for other purposes. Our collection of wake photographs is continually growing, including some showing the detailed bubble structure in a wake.

Neutrino detection
Many noise data sets from AUTEC have been analyzed and various features identified in the spectra.

RESULTS

Sediments
1) Pore-fluid viscosity and the grain-shearing theory of sound waves and shear waves sediments
Fig. 1 shows plots of sound speed ratio and sound attenuation as functions of frequency. The symbols in the plots represent data acquired during the SAX99 experiment in the Gulf of Mexico, the blue lines are the predictions of the GS theory and the red lines represent the new VGS theory. Below 10 kHz, the red lines follow the trends of the data very reasonably, in particular matching the relatively high dispersion displayed by Schock's chirp sonar data (red diamonds). Above 10 kHz, the two theories are essentially the same and both match the data satisfactorily.

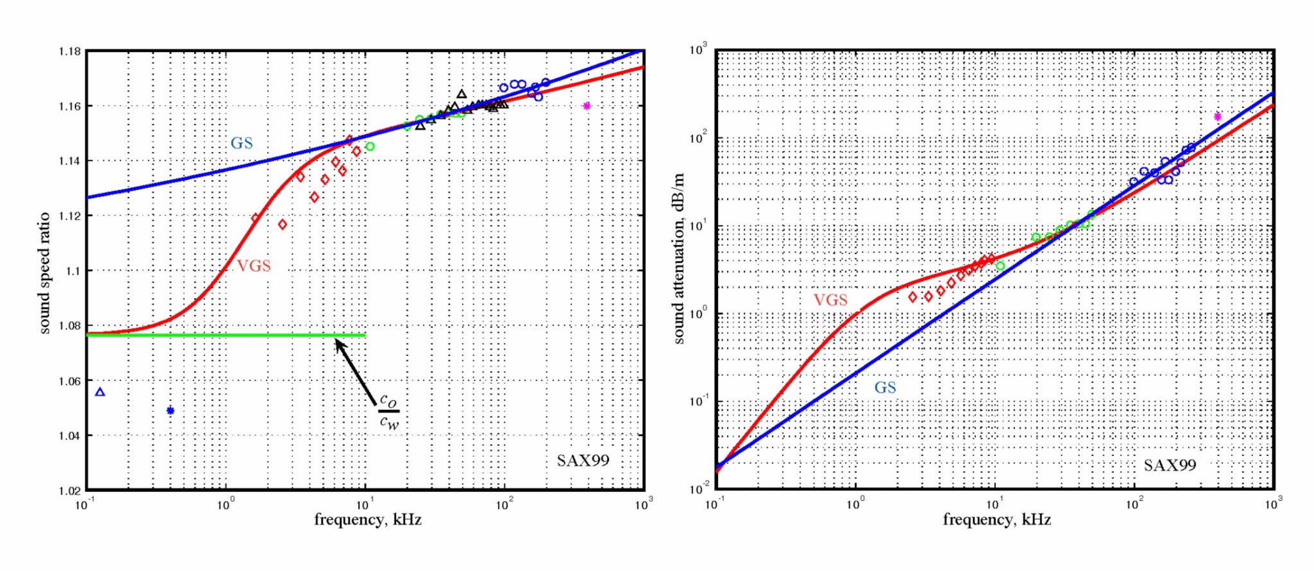

Fig. 1. Sound speed ratio versus frequency (left) and sound attenuation versus frequency (right)

2) Doppler geo-spectroscopy
Preliminary analysis of the MAKAI data indicates that the low-frequency (≈ 100 Hz) sediment sound speed is in the region of 1650 m/s, consistent with expectations for a water-saturated medium sand.

3) Theoretical models of sound from a moving source in a 3-layer waveguide
Complete solutions have been derived for the 2-D and 3-D fields in a Pekeris waveguide in the presence of source motion. As part of both the 2-D and 3-D analyses, new dispersion relations have been derived, allowing the Doppler frequency shifts of the modes to be determined from straightforward algebraic expressions. [JASA, **120**, 1825-1841 (2006)]

4) Geoacoustic inversions for Doppler geo-spectroscopy
Significantly improved spectral resolution has been achieved using adaptive filtering.

5) Grain shape and sediment porosity

Our analysis of the photomicrographs of individual sediment grains yields properties such as cross-sectional area, perimeter and grain shape. From the latter, a Fourier analysis yields a spectrum from which the grain roughness may be deduced. Originally, the whole analysis procedure was quite slow, with each grain taking several hours. Over the past year, the process has been significantly refined, through the development of enhanced software, and now some 500 grains can be analyzed in a morning. In addition, the original measurements of porosity required large sediment samples (bucket size). A technique has now been devised whereby porosity can be measured accurately from a test-tube size sample. This is an important advance, since many of our samples of sand and sediment are quite small.

Deep ambient noise

As the deep ambient noise measurement system has not yet been deployed in the ocean, there are no acoustic data to report.

Ship wakes

An example of the detail that may be seen in high-resolution, aerial photographs of ship wakes is shown in Fig. 2. This particular image was taken from a Cessna 172, with window removed, using a Canon 5D camera with an image-stabilized 28-135mm zoom lens and a circularly polarizing filter to enhance the contrast between the bubbly wake and the bubble-free sea surface. The original 12.8 Megapixel, 16-bit image is of much better quality than the low-resolution version shown here. The spatial distribution of the void fraction in the wake, as seen in Fig. 2, could be the basis of realistic numerical models of acoustic propagation through ship wakes.

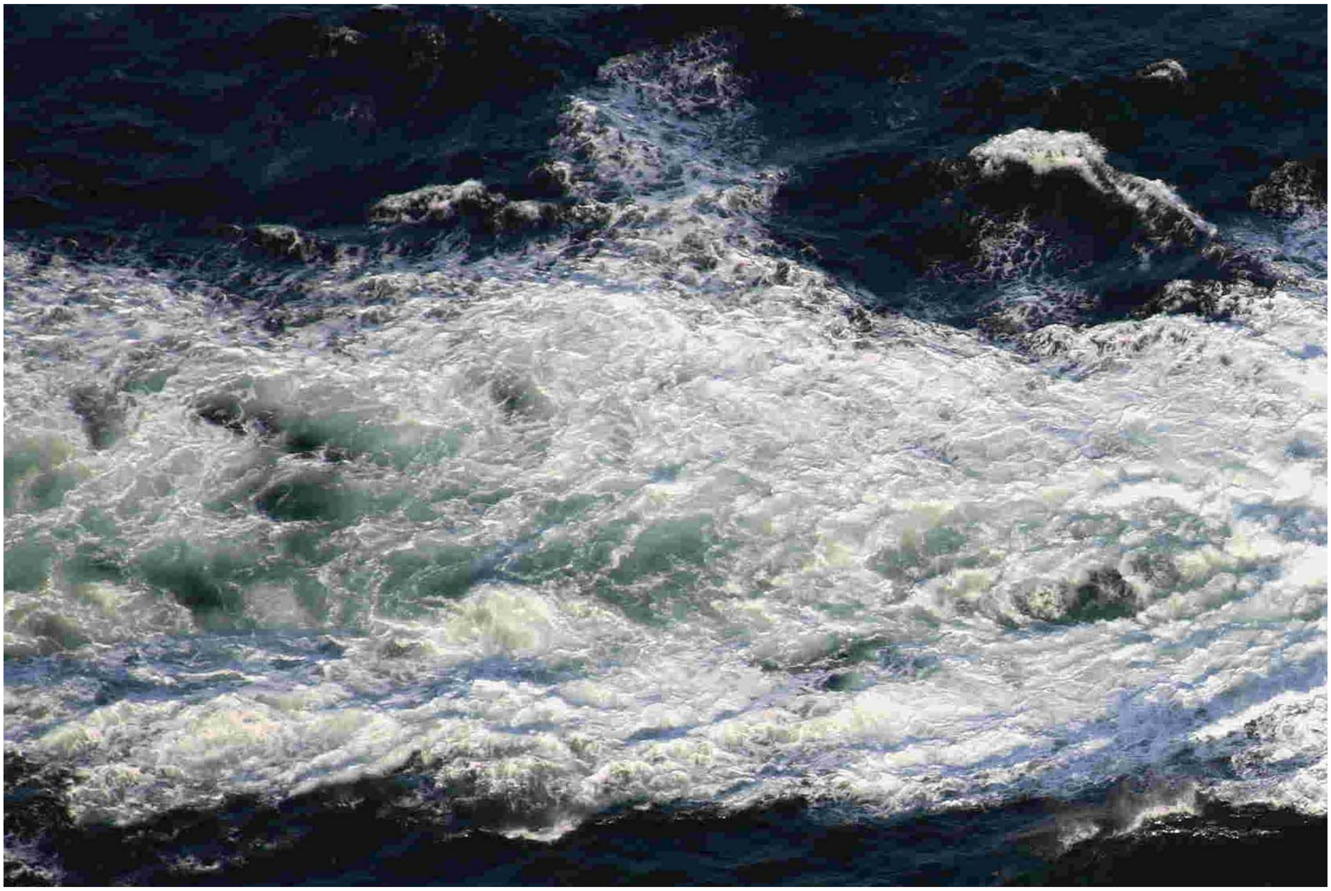

Fig. 2. Detail of the wake from the Morgan Foss, a powerful new Dolphin Class harbor tug. Strong vorticity is evident in the wake and the bubble distribution shows rapid spatial variations, with well-defined regions of high and low concentration.

Neutrino detection
We have not seen any neutrinos yet!

IMPACT/APPLICATIONS

My theoretical and experimental work on the wave and physical properties of marine sediments, and dispersive media in general, is broadly based and has gained a following in the ocean acoustics research community. At ASA meetings and international conferences on acoustics, my theories are cited regularly, suggesting that the work is influencing other scientists in their approach to the complicated issues associated with wave propagation in granular materials.

TRANSITIONS

Several research groups in the USA and elsewhere are using the results of my theoretical work in their own programs, including investigators at the Applied Physics Laboratory, University of Washington, the University of Hawaii, NRL Washington D.C., NRL Stennis and in UK government research

laboratories. This includes my work on ambient noise, waves in sediments, acoustic propagation in shallow ocean channels, sound in multi-layer waveguides, and underwater sound fields from high-Doppler, airborne sources.

RELATED PROJECTS

U.S.A.

1. Dr. Michael Richardson, N.R.L., Stennis, and I are continuing to collaborate on the collection and interpretation of sediment data. I am also closely linked to Dr. Eric Thorsos and the group at APL, University of Washington in connection with sediments and other issues.

2. I have been working with Drs. Michael Porter and Martin Siderius, HLS Research, in helping to plan the MAKAI experiment (selection of sites, etc). I am also helping HLS with research on sediments and ambient noise. Recently, I gave a seminar at HLS on my grain-shearing theory of wave propagation in granular materials.

3. Prof. Giorgio Gratta, Stanford, and I are continuing research on the underwater acoustic detection of extremely high energy neutrinos. Acoustic data for this project are being provided by the U.S. Navy's AUTEC range off Andros Island, Bahamas.

Canada

1. Prof. Ross Chapman, University of Victoria, B.C., and I are collaborating on a shallow water experiment aimed at determining low-frequency (80 Hz to 1 kHz) sound speed and attenuation in marine sediments. In particular, we shall try to use the head wave for extracting the required information. For this frequency band, Ross has a low-intensity air gun source and we use an airborne source of opportunity, two completely different ways of exciting the head wave, but which should yield compatible answers.

United Kingdom

1. Prof. Tim Leighton, Institute of Sound and Vibration Research, University of Southampton, and I are discussing several joint research projects on underwater acoustics. These will involve the inter-change of graduate students, post-docs and perhaps more senior staff between ISVR and SIO. In May 2006, under a UK initiative known as “SETsquared Collaborative US UK Research Programme”, I met Prof. Phil Nelson, Vice Chancellor, University of Southampton, with a view to starting a joint research program between SIO and ISVR. It is not yet clear how this will develop, but under the SETsquared initiative, the UK has funds to supportive such collaborative efforts. (I hold a visiting Professor appointment at ISVR).

2. Dr. Nicholas Pace, University of Bath and I are discussing the possibility of using an airborne source for low-frequency measurements of sediment properties in the Mediterranean.

3. Nathan Price and Gareth Somerset, SEA Ltd. are developing a system for inverting ambient noise measured on a vertical line array to obtain sediment parameters. Their system uses the vertical coherence of ambient noise, as I proposed some years ago, combined with my recent theory of waves in sediments, to yield the majority of sediment properties.

4. Dr Alastair Cowley, DERA, Winfrith is continuing to collaborate with me on phased array techniques applied to acoustic daylight imaging. Several years ago, his team of engineers conducted tests in San Diego Bay using our ADONIS array head of 128 hydrophones with their high-speed beamformer. This phased array system, without the spherical reflector that we used in our original acoustic daylight experiments, yielded recognizable images of targets at ranges of approximately 10 m solely from the acoustic illumination provided by the ambient noise in the ocean.

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Journals & Chapters in Books

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24. M. J. Buckingham, “New theoretical basis for determining the geoacoustic parameters of the seabed,” in *Experimental Acoustic Inversion Methods for exploration of the shallow water environment*, A. Caiti, J.-P. Hermand, S.M. Jesus, and M.B. Porter, Eds. Dordrecht: Kluwer, 2000, pp. 195-209. [INVITED, published, refereed].

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1. D. N. Riches and M. J. Buckingham, “Improvements in or relating to tilt sensors”, Patent No. 3504/78, January 1978.

2. M. J. Buckingham and J. Edwards, “Suspension apparatus”, Patent Application No. 8127155, September 1981.

3. M. J. Buckingham, “Improvements in or relating to sonar systems (HARP), Patent Application No. 8200720, January 1982.

4. M. J. Buckingham, “Acoustic imaging in the ocean using ambient noise”, Patent Application No. 08/012894, Notice of Allowance issued in February 1994.

5. M. J. Buckingham, “Method and apparatus for measuring the speed and attenuation of sound”, 28 November 2003, UCSD Ref. No. SD2004-080-1 [provisional application].

HONORS/AWARDS/PRIZES

1. M. J. Buckingham, Royal Aerospace Establishment, Clerk Maxwell Premium, IERE, U.K., for research on the detection of gravitational radiation (1972).

2. M. J. Buckingham, Royal Aerospace Establishment, A. B. Wood Medal, Institute of Acoustics, U.K. (1982)

3. M. J. Buckingham, Commendation for Distinguished Contributions to Ocean Acoustics at the Naval Research Laboratory, Washington D. C., U.S.A. (1984)

4. M. J. Buckingham, Alan Berman Publication Award from the Naval Research Laboratory, Washington D. C., U.S.A. (1988).

5. M. J. Buckingham, Scripps Institution of Oceanography, Science Writing Award for Professionals in Acoustics from the Acoustical Society of America (December 1997), for the article on “Seeing underwater with background noise”, Scientific American, v. 274 (No. 2), 40-44 (1996).

6. M. J. Buckingham, Scripps Institution of Oceanography, Finalist, Discover Magazine Awards for Technological Innovation, June 1998 (Sight category) for pioneering acoustic daylight imaging.

7. M. J. Buckingham, Scripps Institution of Oceanography, Multiple entries in Marquis Who’s Who and Strathmore’s Who’s Who.

8. M. J. Buckingham,Scripps Institution of Oceanography, Technical Program Chair of the 134th Meeting of the Acoustical Society of America, San Diego, California, 1-5 December 1997.

9. M. J. Buckingham, Scripps Institution of Oceanography, Technical Program Chair of the 148th Meeting of the Acoustical Society of America, San Diego, California, 15-19 November 2004.

My graduate students have been awarded four prizes by the Acoustical Society of America:

1. Thomas Berger, First Prize for Best Student Paper, 136th Meeting of the Acoustical Society of America, 12-16 October 1998: “Low-frequency acoustic emissions of a plunging water jet. Part 1: experiment”.

2. Thomas Hahn, Third Prize for Best Student Paper, 136th Meeting of the Acoustical Society of America, 12-16 October 1998: “Low-frequency acoustic emissions of a plunging water jet. Part 2: theory”.

3. Eric Giddens, First Prize for Best Student Paper, awarded by the Underwater Acoustics and Engineering Acoustics Technical Committees at the 144th Meeting of the Acoustical Society of America, Cancun, Mexico, 2-6 December 2002: “Sound from a light aircraft for underwater acoustic applications”.

4. Eric Giddens, First Prize for Best Student Paper, awarded by the Acoustical Oceanography Technical Committee at the 148th Meeting of the Acoustical Society of America, San Diego, California, 15-19 November 2004: “Geoacoustic inversions in shallow water using Doppler-shifted modes from a moving source”.